Seismic Oceanography

A New Tool to Characterize Physical Oceanographic Structures and Processes

Grant George Buffett

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Seismic Oceanography

A New Tool to Characterize Physical Oceanographic Structures and Processes

Memòria presentada per Grant George Buffett per optar al Títol de Doctor en Geologia

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INTRODUCTION

The worthwhile problems are the ones you can really solve or help solve, the ones you can really contribute something to. No problem is too small or too trivial if we can really do something about it

--Richard Feynman

Scientific problem, motivation and research objectives

Large scale global ocean[1] circulation redistributes heat and freshwater and therefore affects global climate. One of its main forcing mechanisms is, in addition to surface heat and freshwater fluxes, the diapycnal (across lines of equal density) mixing in the ocean interior. The energy needed to drive the mixing processes is mainly provided by tides and wind [Wunsch, 2002]. It is transformed into internal wave energy, cascading through a range of smaller scales leading finally into turbulence and molecular dissipation. Water masses in the ocean are stratified and often separated by relatively thin layers with strong gradients in temperature and/or salinity across which heat and mass transfer occur in order to maintain global circulation and stratification. However, these processes are difficult to observe in practice. Below a few meters, the ocean is opaque to light, and thus to direct optical observations of deep processes [Thorpe, 2005]. Therefore, the development of scientific methodologies and instruments to directly or indirectly measure processes in the ocean interior are of high importance to understanding those processes and their implications.

The motivation behind this research is two-tier: 1) broadly, and academically, it is the scientific curiosity of understanding the ocean in order to better comprehend its role in the context of Earth systems; 2) expressly, the motivation is to develop the methodological toolset necessary to observe the ocean on a spatial and temporal scale not possible with traditional oceanographic techniques, thus allowing the foundation of more accurate models of ocean circulation and thereby, ocean-climate interactions.

The toolset is emerging as a robust technique of physical oceanography known as 'seismic oceanography'. By definition, seismic oceanography is the application of multi-channel seismic (MCS) reflection profiling to physical oceanography. This definition, however, could be subject to future revision and refinement because the development of seismic oceanography observational tools will inevitably lead to newer perspectives. For instance, the method of seismic acquisition may be modified as suggested by

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[1] Throughout this text, the word 'ocean' refers to the sum of the world's major oceans, their connected seas and straits as well as continental shelf waters and inland seas such as the Mediterranean Sea.

Ruddick et al. [2009] such that a weaker, continuous source is used, or it may become applicable to other facets of oceanography (or limnology) such as marine biology or chemical oceanography. In its short history it has already made significant advances into understanding physical oceanographic processes and stands to gain more through further development and application in areas of the oceans where physical oceanographic techniques alone leave gaps in our data and our knowledge. The crucial advantage inherent in the MCS technique is its lateral resolution, which is approximately ten times higher than what is possible with oceanographic instruments alone. However, as will be demonstrated, there are many other advantages to the technique that offer great potential for the study of the ocean.

The study area: Gulf of Cádiz and western Iberian coast.

The Mediterranean Outflow Water (henceforth, MOW) is a natural laboratory for seismic oceanography. The MOW was chosen to test seismic reflection in oceanography for three main reasons: 1) The strong oceanographic signature of the MOW. Due to the penetration of the MOW into the North Atlantic through the Strait of Gibraltar, strong characteristic contrasts in temperature (1.5 °C) and salinity (0.3 psu) and thus, density (0.4 kg/m^3) are observed between the MOW and the surrounding Atlantic waters [Baringer and Price, 1997]. These contrasts in density (along with sound speed) are the contributing factors to reflection coefficient, making the identification of structures and processes possible. 2) The large variety of oceanographic and topographic features, such as a continental slope, undulating seafloor (including seamounts and basins) and meso-scale Mediterranean salt lenses (Meddies). These structures and processes are believed to play an important role in maintaining the temperature and salinity distribution in the north Atlantic [Bower et. al., 1997]. 3) Finally, extensive archived data sets of both oceanographic and seismic data place interpretive constraints on the data collected.

The MOW is a large high salinity tongue of Mediterranean Water (MW) which flows out of the Strait of Gibraltar into the Gulf of Cadiz, forced mainly by density (Figure A). MW, due to the high level of evaporation in the Mediterranean Sea, is more saline, and hence, denser than Atlantic Water (AW) [Richardson et al., 2000]. The MOW cascades down the continental slope and equilibrates at depths between approximately 500 and 1500 m, meanwhile entraining the upper North Atlantic Central Water (NACW) and flowing as a westward guided current called the Mediterranean Undercurrent (MU), while remaining more buoyant than the denser North Atlantic Deep Water (NADW) (e.g. Heezen and Johnson [1969]; Madelain [1970]; Bower et al. [2002]).

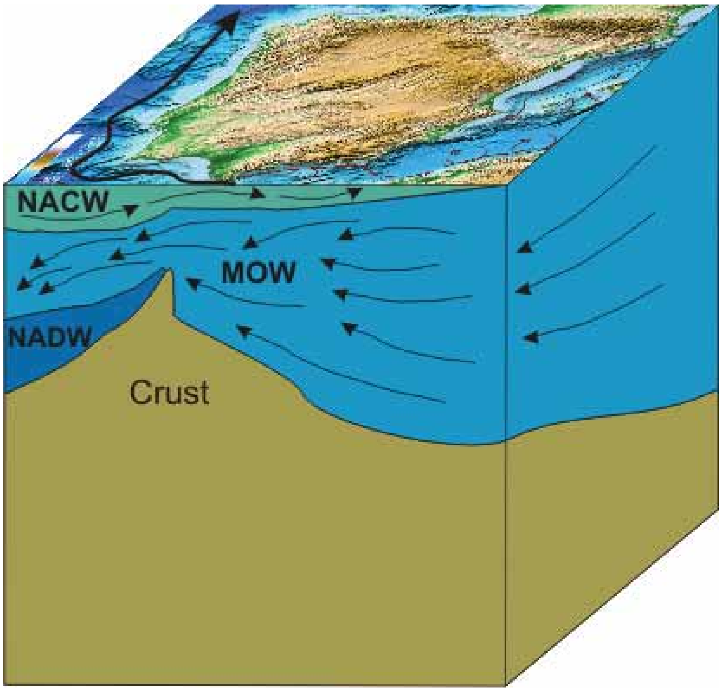

Figure A - Diagram showing the Mediterranean outflow and Mediterranean Undercurrent.

The MU veers north along the coast of Iberia as a result of the Coriolis effect, which describes how angular momentum is conserved on a rotating Earth. Like a moving river, confined by its banks, the MU flows semi-confined by the surrounding Atlantic waters, with which it interacts. One expects that with increasing distance from the MU source, there would be a change in its physical properties due to internal mixing and interaction with surrounding water masses and the continental shelf. Figure B shows the location of all lines analyzed during the study period (July 2006 -November 2010).

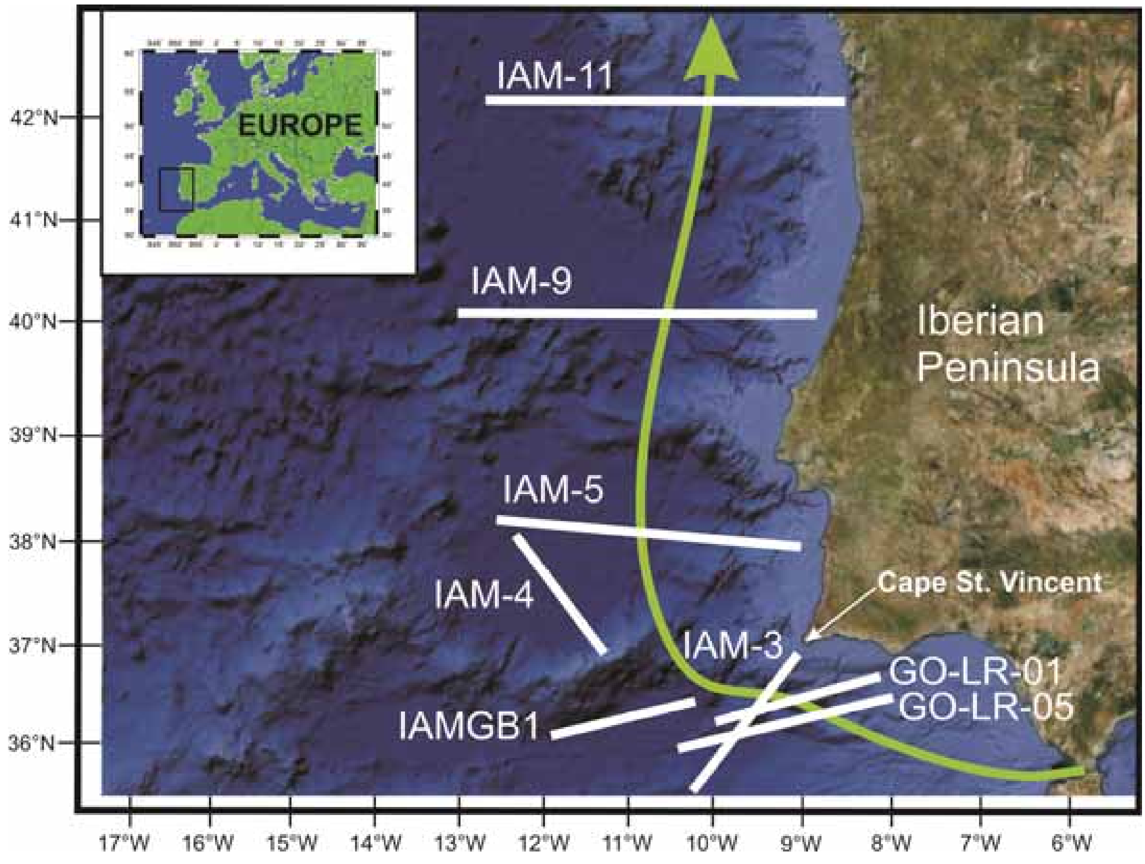

Figure B - Map showing all analyzed lines during the study period. Lines beginning with 'IAM' are from the Iberian Atlantic Margin survey which took place in August and September 1993; Lines beginning with 'GO' are from the GO (Geophysical Oceanography) survey of April and May, 2007.

State of the art : a brief history of seismic oceanography

Ocean dynamics have long been the subject of much interest and the ocean's significance has long been recognized. However, in recent decades we have been able to study the ocean and its dynamics with unprecedented detail and accuracy, telling us more about the physical, biological and chemical processes that control it, how we affect it and how we are affected by it. Modern physical oceanography involves measurements of temperature, salinity and density variations in the ocean as well as the study of waves, tides and currents, the ocean-atmosphere interaction and the properties of seawater such as the propagation of light and sound [Knauss, 1997]. Our ability to construct models that represent objective physical reality regarding ocean processes helps build a comprehensive understanding of the ocean’s role in the distribution of heat around the planet and thereby, the effect this has on climate. A thorough understanding of the ocean permits a more coherent understanding of the role of the global ocean in Earth systems and is therefore essential to a collective understanding of the planet and how society's actions influence it.

As will be shown, seismic oceanography 'sees' contrasts in density and sound speed, or, acoustic impedance contrasts. Density in the ocean depends on three variables: pressure (determined by depth), temperature and salinity. Since pressure in the ocean increases linearly (in the absence of other factors), we look to temperature and salinity variations as the main determinants of density at a given depth. Fundamentally, sound speed[2] (c_{sound}) of a compressional wave varies as a function of the medium's incompressibility, or bulk modulus (K) and density (ρ),

$$c_{sound} = \sqrt{\frac{K}{\rho}} \quad , \qquad \text{eq. A}$$

where K is given by the relation,

$$K = -V\frac{\partial P}{\partial V}, \quad , \qquad \text{eq. B}$$

where V is volume and P is pressure. Therefore at a given depth (pressure) sound speed is fundamentally a function of density. Density in the ocean at a given depth is determined by temperature and salinity, resulting in a complex estimate of sound speed. This is partly because sound speed is proportional to salinity and temperature while density increases in-step with salinity but decreases with increasing temperature. This relationship between temperature, salinity, sound speed and density makes the prediction of temperature and/or salinity directly from seismic data difficult in practice. However, since we know that sound speed is the most important factor influencing reflection coefficient [Sallarès et al. 2009], an accurate estimate of the former through iterative 'velocity analysis' (Section 5.4.7) can be done for this purpose. This is

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[2] I shall refer to the speed of propagation of sound as simply 'sound speed' throughout the text, as opposed to the more common usage in seismology as 'velocity'. This comports with the usage in physical oceanography and reserves the term velocity for actual vectors such as current velocity. Moreover, since the ocean is a fluid where shear waves (S-waves) do not propagate, I shall exclusively refer to sound speed as the speed of sound of pressure waves (P-waves), or those which vibrate in the direction of their propagation.

preferably done starting with a 1-D sound speed profile as a function of depth, which is derived from an in situ probe (XBT, XCTD, CTD – Section 6.2.1). In this manner, it is possible to create accurate seismic maps that can be thus interpreted within the framework of physical oceanographic processes.

Density variations in the ocean affect its dynamics since differences in weight cause pressure differences, which drive motion. Density driven currents are controlled by buoyancy forces and are generally a result of temperature and/or salinity variations caused by heat fluxes at the boundaries of fluids [Thorpe, 2005]. Seismic oceanography methods are sensitive to these density variations because they measure the degree of wave energy reflected from acoustic impedance boundaries. Acoustic impedance is the product of density and sound speed. The reflection coefficient (R) is proportional to the density and sound speed *contrast* across the interface,

$$R = \frac{\rho_2 v_2 - \rho_1 v_1}{\rho_2 v_2 + \rho_1 v_1} \quad . \qquad \text{eq. C}$$

Stronger gradients of density and sound speed mean a higher proportion of reflected energy and a lowered proportion of transmitted energy. The reflected energy is recorded by sensors (hydrophones) near the sea surface and digitally processed to create a large scale ‘reflectivity map’ of the ocean. The high degree of correlation between in situ sound speed measurements and seismic reflectivity is remarkable, demonstrating the potential of seismic reflection profiling as a new tool through which to study the ocean [Ruddick et al., 2009].

There have been numerous attempts to use sound to measure ocean fluid dynamic properties (eg. Obukhov [1941]; Batchelor [1957]; Chernov [1957]; Ottersten [1969]; Tatarski [1971]; Munk and Garrett [1973]; Brandt [1975]; Goodman [1990]; and Ross and Lueck, [2003]). Brandt [1975] studied high-frequency sound scattering from density variations of a turbulent saline jet in the laboratory. He concluded that the observed scattering was a result of acoustic impedance fluctuations produced by the jet and therefore surmised that acoustic imaging techniques could be used to study oceanic diffusion processes and thermohaline structures. Orr and Hess [1978] acquired a joint physical oceanography/high-frequency acoustic backscatter dataset and reported that at depths corresponding to the maximum temperature gradient there was increased backscatter intensity, concluding that oceanic microstructure was responsible.

Following this work, Haury et al. [1983] provided further constraints on the relationship between oceanic microstructure and acoustic backscatter. By combining the methods of Orr and Hess [1978] with plankton measurement constraints, they were able to produce an acoustic snapshot of a breaking internal wave, identifying thermohaline fine structure as the source of the backscatter. Munk and Wunsch [1979] first used travel-time ocean acoustic tomography by adapting a technique used in seismology to image the interior of the earth to represent large scale ocean structures. Thorpe [2005] describes backscatter reflection from turbulent microstructure in the frequency range of 100-200 kHz stating that the acoustic return from a 'clear water' scattering region, meaning one devoid of algae, bubbles or particles, depends on range and attenuation in the water column as well as the acoustic cross-section of the scattering volume, in addition to sound frequency.

The first reported observations of ocean reflectivity from MCS reflection profiling came from Gonella and Michon [1988] and Phillips and Dean [1991], but neither group associated it to thermohaline finestructure. Water column reflections were also reported in the acquisition summary (noted as a curiosity) during the seismic data analyses stages of the Iberian-Atlantic Margin (IAM) survey in the Gulf of Cadiz, Gorringe Bank at the EU Large Scale facility at GEOMAR but were never analyzed further. In fact, it is still commonplace within the geophysical community to consider the ocean as homogeneous, at least to the degree of accuracy of seismic surveys. To geophysicists and geologists in search of hydrocarbons or in study of the solid Earth, the ocean is an inconvenient nuisance that is generally muted (or not recorded at all by delaying the start of recording by several seconds). It was not until the recent serendipitous re-discovery by Holbrook et al. [2003] of ocean reflectivity during a seismic cruise off the east coast of Newfoundland, that significant interest arose and research began in earnest toward MCS as a tool of physical oceanography. Holbrook and colleagues delved much deeper into the seismic data than previous authors to find that distinct water masses could be mapped and their internal structure imaged to depths of at least 1000 m, in much the same way as for the solid Earth. This resulted in striking visual images of large eddies and filaments of interleaving water masses. They then deduced that the images represented an oceanic front, possibly between Labrador Sea Water and Norwegian-Greenland Overflow Water of the Deep Western Boundary Current. Ruddick [2003] then explained the intrusions observed by Holbrook et al. [2003] as related to double-diffusion processes.

Nandi et al. [2004], using newly acquired seismic and in situ temperature data (XBT) from the Norwegian Sea, followed upon the work of Holbrook et al. [2003] and established a direct correlation between reflection amplitudes and temperature contrasts as small as 0.03°C, demonstrating the method's high sensitivity.

In 2005 there were at least four publications in seismic oceanography starting with the news article in EOS by Géli et al. [2005] which presented seismic data acquired off the Brazilian margin in 2004. Tsuji et al. [2005] published the first application of seismic oceanography to image the Kuroshio Current off the coast of Japan showing that coherent fine structure could persist for at least 20 days. Holbrook and Fer [2005] made the first successful attempt to image internal waves using seismic techniques and later, Páramo and Holbrook [2005] demonstrated the applicability of Amplitude-vs-Offset (AVO) methods to measure temperature contrasts.

Nakamura et al. [2006] continued the work of Tsuji et al. [2005] on the Kuroshio Extension Front off Japan, but added the use of in situ temperature and salinity and current velocity measurements to corroborate it. They found that synthetic seismograms created from temperature and salinity measurements compared favorably with independent seismic data.

In 2007 acquisition for the first large-scale joint seismic and oceanography project, GO (Geophysical Oceanography), started in the Gulf of Cadiz. The GO project included participation from eight separate European research institutions from The United Kingdom, France, Italy, Germany, Spain and Portugal. It was carried out with two ships, the British ship RRS Discovery and the German vessel FS Poseidon, conducting high and low resolution seismics coincident and simultaneous to the launching of in situ probes, along with Acoustic Doppler Current Profilers (ADCP) and ocean bottom seismometers (OBS) among other oceanographic tools. A 2D+time profile was obtained by repeatedly acquiring a seismic transect in the same geographic location to observe how quickly thermohaline structure changed. Large structures were found to change noticeably in as little as four hours. The GO project, which was the first attempt to calibrate MCS in the context of oceanography, led to subsequent publications and a heightened international interest in seismic oceanography.

Krahmann et al. [2008] derived horizontal wave number spectra from Iberian Atlantic Margin (IAM) seismic profiles, thereby developing some of the tools necessary to estimate internal wave energy directly from seismic data. Kormann et al. [2008] provided a method to recover simulated reflected data with a degree of sensitivity of one order of magnitude better than what is observed in actual physical phenomena. Wood et al. [2008] performed the first 1-D full-waveform inversion of seismic reflection data to obtain estimates of temperature. Biescas et al. [2008] (Chapter 4) provided the first seismic imaging of a Meddy and made the connection to double-diffusive processes at its margins. International and interdisciplinary cooperation flourished at the first European Science Foundation Exploratory Workshop on Seismic Oceanography (SOW), which included researchers from countries within the EU (France, U.K., Germany, Spain, Italy, Portugal and Ireland) and around the world (Canada, U.S.A., China and Japan).

Ruddick et al. [2009] put forward the idea of seismic images as maps of the temperature gradient. Their publication in Oceanography Magazine made headway to alleviating the general skepticism of some oceanographers toward the seismic reflection method. Buffett et al. [2009] (Chapter 1) analyzed seismic data from along the trajectory of the Mediterranean Undercurrent, observing the correlation between decreasing seismic amplitude and decreasing temperature and salinity values as a function of distance from its source at the Strait of Gibraltar. They deduced that the processes responsible for the progressively diminishing seismic amplitudes within the Undercurrent were mixing and entrainment processes. Next, Blacic and Holbrook [2009] performed the first analysis on a 3D dataset and estimated the orientation of internal waves. Finally, a special section in Geophysical Research Letters was published, entitled "Seismic Oceanography: A New Tool to Understand the Ocean Structure". This brought together a wide spectrum of research from initiates in the field (Geophysical Research Letters, vol. 36, no. 24, 2009). In the said volume Fortin and Holbrook [2009] addressed sound speed requirements for optimal imaging of seismic oceanography data, Géli et al. [2009] explored the limits of high-resolution sources and showed that there is appreciable short scale temporal variability of thermohaline fine structure in as little as four hours, Hobbs et al. [2009] measured the effect of the seismic source bandwidth, Holbrook et al. [2009] imaged internal tides near the Norwegian continental slope, Klaeschen et al. [2009] estimated reflector movement, Kormann et al. [2009] investigated acoustic modeling, Krahmann et al. [2009] evaluated seismic reflector slopes with a Yoyo-CTD, Ménesguen et al. [2009], through numerical simulations, investigated the effect of seismic bandwidth on rotating, stratified turbulence of an anticyclonic eddy, Sallarès et al. [2009] (Chapter 4) determined the relative contribution of temperature and salinity to ocean acoustic reflectivity, Sheen et al. [2009] estimated mixing rates from seismic images and Vsemirnova et al. [2009] estimated internal wave spectra using constrained models of the dynamic ocean.

In late 2010 at the time of this writing there have been contributions from Quentel et al. [2010] whom characterized mesoscale and sub-mesoscale structures in Mediterranean Water and Buffett et al. [2010] whom applied stochastic methods to seismic oceanography data to estimate scale lengths. Most recently, Biescas et al. [2010] and Fer et al. [2010] both imaged thermohaline staircases and Pinheiro et al. [2010] imaged the MOW and meddies off western Iberia.

It is clear from the high intensity of publication in seismic oceanography that it is quickly being recognized as an important tool to study oceanic thermohaline finestructure. However, notwithstanding the abovementioned, the ocean has not been extensively explored with seismic waves, although many reflection seismology surveys have been conducted over the oceans to explore the solid Earth for several decades. These surveys pertained to the collection of crustal and deep solid Earth data for use in (especially) petroleum exploration and (less so) for purely academic studies such as in plate tectonic research.

This work deals with imaging thermohaline finestructure within the ocean, not the solid Earth, but some of the data contained herein (the IAM Survey) were acquired in the context of solid Earth studies. Other datasets not included in this volume show various intensities of thermohaline finestructure from weak, diffuse reflectivity to strong reflectors that are laterally coherent for hundreds of kilometers. The reason for the disparity in data quality between datasets may be due to the acquisition parameters having been customized to image the solid Earth and thus, for various reasons (e.g. low frequency content; non-optimal shot or receiver spacing), were not sensitive to the comparatively weak reflectivity of the ocean. Alternatively, the non-appearance of reflectivity in the water column in a given part of the ocean may simply be due to the fact that thermohaline acoustic impedance contrasts are too weak or effectively non-existent to be observed[3]. Some of these variables can be partly constrained by fine-tuning the seismic method to be highly sensitive to ocean reflectivity and thus perhaps less so to crustal reflectivity. This approach is currently being done in all new exclusively seismic oceanography studies (e.g. The GO Project). New seismic oceanography surveys may also take place as so-called 'piggy-back' surveys [Ranero et al., 2010], where the seismic oceanographer has no control over the survey parameters, but has access to the dataset and may jointly acquire in situ oceanographic data as constraints on later analysis. However, analysis of historic or archived datasets are limited by the data they contain. In this case, novel processing techniques are being developed in order to extract as much information from the data as possible. Success in this approach will offer valuable insights into past and present ocean circulation such that we may hope to understand how the ocean is changing contemporaneously and what the implications are for that change in the context of the ocean dynamics and global climate change.

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[3] Ubiquitous on all seismic sections in this thesis in the deep water abyssal zone known as the North Atlantic Deep Water which, to the limit of the measurement, is transparent to seismic waves. Since notable reflectivity is observed in shallower waters, this is likely a result of more homogeneous (and therefore, well-mixed) waters at depth.

Thesis layout

The objective of a doctorate thesis is to present original research. In this respect, Part I of this thesis consists of two peer-reviewed papers published by the author and co-authors (Chapters 1 and 2), one manuscript submitted for publication (Chapter 3) and two published peer-reviewed research letters that the author played a lesser role developing (Chapter 4). Part II of the thesis addresses the seismological (Chapter 5) and oceanographic backgrounds (Chapter 6) in the context of some of the structures and processes that are amenable to seismic ensonification. This section is not intended as a complete work on those respective topics, but rather to guide the uninitiated reader to the references therein such that they may pursue lines of research of their own interest. Part III consists of general discussions and conclusions (Chapter 7) and potential future research and development (Chapter 8). Appendix I consists of a summary of the thesis in the Catalan language, Appendix II presents the precise seismic processing flows conducted by the author, Appendix III contains fold-out style broadsheets of the seismic sections, which are not well-represented on typical A4 paper and Appendix IV includes a useful glossary of terms to help bridge the gap between for readers not initiated in either seismology or oceanography.